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A Paradigm Lost: New Theories for Aspherical PNe

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Abstract. Theoretical Models for the shaping of PNe are reviewed in light of new high resolution images. The new data indicate the purely hydrodynamic interacting stellar winds model can not recover the full variety of shapes and kinematics. New models, some speculative, others more firmly grounded are discussed. In particular, accretion disks and magnetic fields are identified as two of the most promising avenues of future research. Outstanding issues such as jet formation by PNe disks and dynamo activity in P-AGB stars remain to studied. Finally, new simulations of the Egg Nebula are presented as an example of a "paleontological" study designed to recover the history of an individual object.

1. Introduction

In the last decade Planetary Nebulae (PNe) have gone from mysterious to mundane and back again. Ten years ago the variety of PNe shapes was seen as puzzling and lacked a unified physical theory. Five years later it appeared that the needed theoretical interpretation had been found in the Generalized Interacting Stellar Winds (GISW) model. The wealth of new, high resolution space and ground based observations of PNe has made the GISW paradigm seem less universal than once hoped for and these objects once again present us with significant puzzles and theoretical challenges. It is remarkable that such a common phenomena as the end stages of low and intermediate stars should so consistently surprise and outwit us. In this paper my aim is to review the state of aspherical PNe theory. I am particularly interested in where the new observations show the limits of the GISW model and where, in my opinion, the next generation of theoretical models is likely to emerge.

2. Observations Outpace Theory: Limits of the GISW Model

Researchers in this community are, by now, well aware of the main contours of the GISW model. I repeat them for completeness (for more details see Kwok *et al.* 1978, Kahn & West 1986, Balick 1987, Icke 1988 and also Frank 1999 for a review). The defining paradigm for explaining aspherical PNe posits a single star evolving from the AGB to a white dwarf. As the star evolves so does its wind. A slow (10 km s^{-1}), dense (10^{-4} M$_\odot$) wind expelled during the AGB is followed by a fast (1000 km s^{-1}), tenuous (10^{-7} M$_\odot$) wind driven off the contracting proto-white dwarf during the PNe phase. The fast wind expands into the slow

wind shocking and compressing it into a dense shell. The "Generalized" part of this interacting winds scenario occurs when the AGB wind assumes a toroidal geometry with higher densities in the equator than at the poles. Inertial gradients then confine the expanding shock leading to a wide range of morphologies. Numerical models (Soker & Livio 1988, Mellema *et al.* 1991, Icke *et al.* 1992, Frank & Mellema 1994, Mellema & Frank 1995, Dwarkadas *et al.* 1996), have shown this paradigm can embrace a wide variety of nebular morphologies including (and this point needs to be stressed) *highly collimated jets* (Icke *et al.* 1992, Frank & Mellema 1997, Mellema & Frank 1998, Borkowski *et al.* 1997). In spite of the success of these models, high resolution observations, primarily from the HST, have revealed new features of PNe morphology which *appear* difficult to recover with the classic GISW model. Below I list what I consider to be the most vexing issues raised by these observations.

Point-symmetry: This morphological class was first identified by Schwarz *et al.* 1992. It is most striking in PNe where jets or strings of knots are visible. There are however many bipolar (and even some elliptical) PNe which also show point symmetry in their brightness distributions. It has been suggested that point symmetry occurs due to precession of a collimated jet (Lopez 1997). If this is the case it is difficult to imagine that a large-scale out-flowing gaseous torus (needed for GISW) can provide a stiff precessing nozzle for the flow. Inhomogeneities in the torus would tend to smooth out on sound crossing times of $\tau = L/c \approx 10^{17} cm/10^6 cm\ s^{-1} \approx 3 \times 10^3 y$. This is on order of, or less than, many of the inferred precesession periods.

Jets and Ansae: While the GISW model *can* produce narrow jets it usually requires a large-scale "fat" torus. It is not clear if such structures exist in PNe (this point requires further study). The FLIERS/Ansae described by Balick *et al.* 1997 are more problematic in that they have, so far, resisted most attempts at theoretical explanation (see however Mellema *et al.* 1998) .

Multi-polar/Episodic Outflows: A number of PNe show multiple, nested bipolar outflows (Guerrero & Manchado 1998, Welch *et al.* 1999). In some cases these multiple bipolar shells have common axii of symmetry, while in others the axii are misaligned (multi-polar). Such objects present problems both for the GISW model and the "classical" view of post-AGB evolution. When the nebulae is multi-polar it is usually point-symmetric and presents the same challenges described above. In some cases (Kj PNe 8, Lopez *et al.* 1997) it appears as if the development of dense torus may occur more than once with separate axii in each case. Such a phenomena is difficult to reconcile with either a classic single-star model or appeals to binary scenarios. The most likely explanation for any multiple bubbles whether uni- or multi-polar is an episodic wind. A fast wind occurring in outbursts or varying periodically is not part of the standard model for post-AGB evolution (though a nova-like recurrence is possible in binary systems). These nebulae may originate from born-again PNe however the time-scales for the bubbles ($< 10^4$ y) do not appear well matched with He shell inter-pulse timescales.

Post-AGB (P-AGB)/Proto-PNe (PPNe) Bipolar Outflows: One of the most startling results of the last five years is the recognition that fast (≥ 100 km s^{-1}) bipolar outflows can occur in the PPNe or even the Post-AGB stage. Objects like CRL 2688 and the Red Rectangle raise the question of how

high-velocity collimated flows occur when the star is still in a cool giant or even supergiant stage (CRL 2688 has an F Supergiant spectral type: Sahai *et al.* 1998; Young *et al.* 1992). The origin of the wind in this early stage and the mechanisms which produce its collimation are critical questions because it appears that much of the shaping of PNe may occur before the "mature" PNe phase when the star has become hot enough to produce a strong ionizing flux (Sahai & Trauger 1998).

3. New Physics

In spite of its successes, it appears that the GISW model can not embrace the full range of behaviors observed in PPNe and PNe. In this section I briefly review (or suggest) some alternative scenarios for PNe evolution. In all cases the scenarios focus on the source of the outflow, either the nascent Central Star of a Planetary Nebulae (CSPNe) or an accretion disk surrounding the star.

3.1. Common Envelope Evolutionary Truncation (CEET)

The "story" of PNe evolution has long included the possibility of a common envelope phase (Iben & Livio 1993, Soker 1998). When a giant star swallows a companion the pair's common envelope can be rapidly ejected (most likely in the orbital plane) leaving either a merged core or a short period binary. This process need not occur at the tip of the AGB when the giant's stellar core has already evolved to a CSPNe configuration. Common envelope ejection can occur at any point in the evolution along the AGB (or RGB) branch. The initiation of the CE evolution depends on the size of the star *and* the orbital separation of the binary. Thus the envelope of the star can be torn off the core exposing it before it is in a stable CSPNe configuration.

 If the core is not yet "prepared" to be a CSPNe then we might expect instabilities that could lead to rapid and violent ejection of material remaining in the atmosphere. This could provide a source of explosive energy release. This is an attractive idea because it may explain the fully non-asymmetric structures such as the elephant trunks seen in some PPNe and very young PNe (Trammel, these proceedings). For an exposed core of mass M_c with a remnant envelope of mass M_e the time-scale for thermal instabilities can be crudely represented as the Kelvin-Helmholtz timescale (Kippenhahn & Weigert 1989) For typical CSPNe this is $\tau_{KH} < 10^3$ y, a short fraction of the AGB evolutionary timescale. Thus these instabilities could occur rapidly allowing them to escape direct detection. Note also that if these stars have a strong dynamo acting then the loss of the envelope could expose the kG fields at the base of the convective zone on short timescales such that magnetic instabilities could act as the source of explosive energy release.

 Finally, consider the possibility that the secondary does not spiral all the way in to merge with the core but leaves instead an extremely close binary (with separation a). In the period just after the CE ejection the two stars will orbit rapidly in a environment still rich with circumbinary gas (Sandquist *et al.* 1998). Spiral shocks driven by the secondary's orbital motion will heat the gas to temperatures proportional to the V_k^2 where V_k is the Keplerian speed of the secondary. If the cooling time t_c for the gas is greater or equivalent to its

sound crossing time t_x then the pressure gradients will set the gas in motion. It is possible therefore that the close binary will produce a kind of *egg-beater* effect driving a wind from the source at speeds

$$V_w = \zeta V_k = \zeta \sqrt{GM_c/a} \qquad (1)$$

In the equation above $\zeta \leq 1$ and would depend on the ratio of t_c/t_x.

While this CEET scenario is highly speculative it may provide routes for either explosive energy release or winds in the PPNe stage. In lieu of other mechanisms for driving relatively fast winds from cool PPN stars (Simis, Dominik & Icke, these proceedings) this feature makes the CEET a scenario worth further exploration.

3.2. Accretion Disk Winds

The possibility that accretion disks play a role in PNe formation was first suggested by Morris (1987). More recently Soker & Livio (1994) and Reyes-Ruiz & Lopez (these proceedings) have explored the formation of disks in binary PNe systems in more detail. In these works there has been a tacit assumption that disk = outflows. Obviously there is gap in the theory and it remains unclear if or how accretion disks in PNe can create collimated outflows that match observations. I now review two classes of disk wind models that may be applicable for PNe.

Magneto-centrifugal Launching: The potential for accretion disks to create strong, collimated winds has been explored in some detail by the both the YSO and AGN communities (Ouyed & Pudritz 1997, Shu *et al.* 1994). The most popular models rely on the presence of magnetic fields embedded in the disk (*ie.* the foot points of the field are tied to the disk via surface currents). The field co-rotates with the disk. If field lines are bent at an appropriate angle to the disk axis ($\theta > 30^o$) energy can be extracted from rotation and matter loaded on the field lines is flung outward "like a bead on a wire". This mechanism has been shown effective in both analytical and numerical studies. While it is clear that the mechanism can produce winds on the order of the escape speed at the launch point, the geometry of the wind that is generated is still uncertain. Some studies indicate that a narrow jet of hypersonic plasma will form almost immediately above the disk/star system (Ouyed & Pudritz 1997). Other researchers (Shu *et al.* 1994) find the collimation process to be slow leading to so-called "wide-angle" winds with cylindrical density stratification (the densest parts of the flow lie along the axis giving the appearance of a jet).

Magneto-centrifugal launching has many attractive features for PNe. For instance the presence of narrow jets in the midst of wider bipolar flows might be naturally explained by wide-angle wind models. The issue which must be addressed is, can such flows be established in PNe disk systems? YSO and AGN disks have typical size scales of hundreds of AU. A PNe disk could have a size scale of order the Roche Lobe. Can the appropriate physics be obtained in these smaller disks? For example, can magnetic fields of the right magnitude and geometry be generated in these disks? Finally, can the flows from the disk produce the observed morphology and kinematics of the nebulae? Recent MHD jet propagation studies using magneto-centrifugal launching models as input

show promising results in terms of generating diverse flow characteristics (Frank *et al.* 1999) however such research remains in its infancy.

It is, at least, possible to estimate the terminal speed of a magneto-centrifugal disk wind as

$$V_\infty \approx \Omega(r) r_A(r) \tag{2}$$

where $\Omega(r)$ is the rotation rate in the disk at radius r and the $r_A(r)$ is the Alfvén radius of the flow launched at that disk radius. Typically r_A is of the order of a few times r (Pelletier & Pudritz 1992). Thus assuming a keplerian disk with a characteristic size of order the stellar radius for a P-AGB star ($r \approx R_\odot$), the equation above yields $V_\infty \approx 100 - 1000 km/s$ which is of the order observed in PNe jets. Thus the application of MHD disk-wind models to PNe could be a promising field for future work (Frank *et al.* 1999).

Radiation-driven Disk Winds: Even without magnetic fields accretion disks can generate outflows. Angular momentum must be dissipated in order to allow material in the disk to spiral inward. Thermal energy created in the dissipational process can heat the disks' surface layers to high enough temperature for line driving to become effective. A wind is then driven off the surface of the disk in the same manner as one is produced by a hot star.

In a series of numerical models Proga and collaborators (Proga, Stone & Drew 1998) have explicated the properties of radiative disk winds. They find the winds emerge with a conical geometry with large half-opening angles of $\theta > 45^o$. It is noteworthy that the flow pattern in the winds can be unsteady. In general the maximum mass loss rates in these models tends to be low ($\dot{M} < 10^7 \ \mathrm{M_\odot \ yr^{-1}}$) and are associated with high wind velocities ($v_w > 1000 \ \mathrm{km \ s^{-1}}$). Thus these winds would likely produce fairly wide lobed energy conserving bipolar outflows. Application of these models to the short lived accretion disks which would likely occur in PNe have not yet been attempted and further study in this area may prove fruitful.

3.3.   Magnetized Wind Bubbles

One of the most promising new theoretical models invokes a toroidal magnetic field embedded in a normal radiation driven stellar wind. This so-called *Magnetized Wind Bubble (MWB)* model was first proposed by Chevalier & Luo (1994) and has been studied numerically by Rozyczka & Franco (1996) and Garcia Segura *et al.* (1999). In these models the field at the star is dipolar but assumes a toroidal topology due to rapid stellar rotation. When the wind passes through the inner shock, hoop stresses associated with the toroidal field dominate over isotropic gas pressure forces and material is drawn towards the axis producing a collimated flow. This mechanism has been shown capable of producing a wide variety of outflow morphologies including well collimated jets. When precession of the magnetic axis is included in fully 3-D simulations, the MWB model is capable of recovering point-symmetric morphologies as well (Garcia-Sequra 1997). The capacity for the magnetic field to act as a long lever arm imposing coherent structure across large distances makes these models particularly attractive.

The potential difficulties involved in application of the MWB models include the presence of field reversals at the "equatorial current sheet" (which need not be restricted to the equator) where reconnection could produce strong dissipation of the magnetic field (Soker 1998, Frank 1999). A more serious difficulty involves

the rather extreme input parameters required for the hoop stresses to become effective. The critical parameter in the MWB model is the ratio of magnetic to kinetic energy in the wind, σ. In terms of parameters at the stellar surface

$$\sigma = \frac{B^2}{4\pi\rho_w V_w^2} = \frac{B_*^2 R_*^2}{\dot{M}_w V_w}\left(\frac{V_{rot}}{V_w}\right)^2 \tag{3}$$

where V_{rot} is the rotational velocity of the star. The MWB model is only effective when $\sigma > .01$. It has been noted that this value is what obtains in the Sun. While such an identification may seem initially seem promising for the model one must recall that the $\dot{M}_{PN}/\dot{M}_\odot > 10^7$! Thus the additional factor of ten million or more must be made up by some combination of field strength, rotational velocity or stellar size. Unfortunately these are usually anti-correlated. Given that $\dot{M}$ is fairly well established it appears that one needs either very strong fields or very high rotation rates.

The situation becomes more difficult when one considers that without significant angular momentum transport in the star, mass losing AGB stars should spin-down during their evolution. Consider the simplest case of a constant density star rotating as a solid body. One can show that given a main sequence rotation rate, mass and radius of Ω_{ms}, M_{ms} and R_{ms} respectively, the post-AGB rotation rate will be

$$\Omega_P = \Omega_{ms}\left(\frac{R_{ms}}{R_P}\right)^2\left(\frac{M_P}{M_{ms}}\right)^{2/3} \tag{4}$$

where P denotes Post-AGB quantities. Note that since $M_P < M_{ms}$ and $R_P > R_{ms}$ we will always have $\Omega_P < \Omega_{ms}$.

It has been argued that effective mixing between the core and the envelope during the AGB stage can produce high surface rotational velocities (Garcia-sequra *et al.* 1999). While this may be possible it's effectiveness would tend to diminish dynamo processes which may be needed to create the magnetic field.

3.4. Dynamos

If magnetic fields play a role in post-AGB and PNe evolution then one must address the source of the field. While it is possible that dynamically significant fields may be preserved as fossil relics from the main sequence, it is more likely that the fields may be generated via dynamo processes. The standard $\alpha - \omega$ mean field dynamo model used to explain most astrophysical magnetic fields (stellar, galactic etc.) relies on a combination of convection and differential rotation. The rotation stretches the field lines while convection turns toroidal components into a poloidal (dipole-like) field. The effectiveness of a dynamo can be expressed in terms of the dynamo number N_D (Thomas, Markiel & Van Horn 1995),

$$N_D \propto \Delta\Omega\frac{r_c}{L} \tag{5}$$

where $\Delta\Omega$ is the differential rotation which occurs over a scale L in the midst of a convection zone of size r_c. Effective dynamos in AGB, post-AGB or CSPNe require $N_D > 1$. The equation above shows the difficulty of using a rapidly rotating star whose angular momentum has been well mixed as the source of

strong magnetic fields. Unless the field is a fossil of the previous stages, dynamo generated fields require strong differential rotation.

There remains much work to be done in the application of dynamo theory to AGB stars (Pascoli 1997). The growing implication that MHD is a necessary part of the nebular dynamics is likely to require that such work be done.

4. Nebular Paleontology

There are many examples of PNe studies in which attempts have been made to directly link simulations with data via synthetic observations. These have usually involved calculation of various optical forbidden and permitted line intensity maps. As this approach matures it should become possible to carry out stellar wind paleontology studies in which the history of an individual object is reconstructed based on its morphology, kinematics, ionization and chemical structure.

For such studies to be successful they require objects that have been very well characterized observationally (η Car, SN1987A; Collins et al 1998). The Egg Nebula is becoming one such object. Figure 1 presents the results of a paleontological study of the Egg nebula (Delamarter *et al.* 1999) in which simulations that included H_2 chemistry and excitation as well as post-processed scattered light image production were carried out. After more than 50 simulations we found that the GISW model could *not* recover the observed features of the Egg. Further simulations showed that the best fit to H_2 and scattered light intensity maps required a torus ejected at about the same time as a fully collimated jet. The torus and jet were distinct, non-interacting dynamical features. Based on the requirement that H_2 not become dissociated the results allowed for reasonably unique determination of the mass loss history of the central star. We note in Fig 1, however, that these models could not recover the unusual tuning-fork pattern seen in the scattered light images of the Egg. The images did produce a good match to other PPN such as IRAS 17150-3224.

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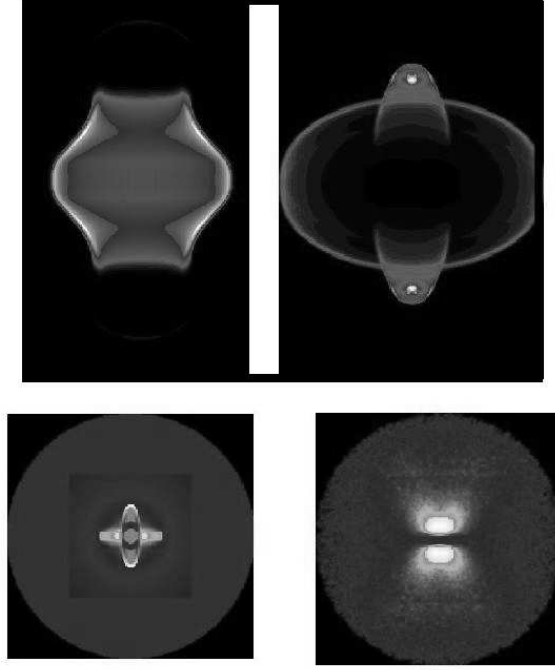
Figure 1.   Results of hydrodynamic simulations of the Egg Nebulae. Bottom Left: Log density for a torus + jet model. A torus of high density gas ejected during the P-AGB phase expands into a spherically symmetric AGB wind. The torus is followed by a well collimated jet propagating along the symmetry axis. The square contours are an artifact of an expanded grid. Bottom Right: Scattered light image taken from this simulation. Upper Right: H_2 image of a torus + jet model. Note how shock emission at the edge of the torus defines a ring. Upper Left: H_2 image of a GISW model. Note that the model fails to capture the salient properties of the Egg.